Novel Application of a Crystal Process Controller and DOE to Improve Metallizing Results

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ABSTRACT

A quartz crystal process controller has been adapted to control a 1.8 meter diameter production metallizer with greater flexibly and reproducibly than the standard configuration. Since the approach in metallizing is commonly that of completely evaporating a measured charge of aluminum, the thickness monitoring aspect of the controller was overridden and only the power ramp and soak capabilities were employed. A challenge is presented by parts which are deeper in proportion to their aperture than is ordinarily considered practical for metallizing in this type of equipment. The close distances to the filaments of the densely packed parts, the excess thickness of coating in some areas, and the steep angles of the surfaces to the incoming material tended to cause discoloration. Adequate coverage in the depths of the part require large charges of aluminum and long firing cycles. Design of Experiments methodology can be employed to find the best controller program parameters to give good part coverage, high reflectance, and long filament life. Practical results have been achieved by the approaches described.

THE PROBLEM

A great variety of parts are metallized with aluminum in regular production. These processes utilize different tungsten filaments and different charges of aluminum per filament, depending on the parts to be coated. Parts which have deep cavities such as that shown in cross-section in Fig. 1 are notoriously difficult to metallize in the commonly used equipment. This is particularly true when they have depths equal to or greater than the opening of the cavity to be coated.

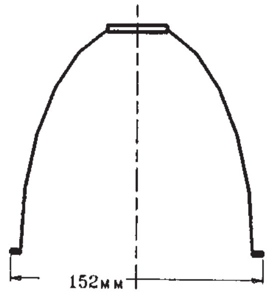

Fig.1. Cross section of a deep cavity reflector part.

It is difficult to obtain adequate coverage in the depths of the cavity of the part without having discoloration on areas which are at steep angles and close to the filaments. Large charges of aluminum and long firing cycles are needed to achieve the needed coverage.

A typical 1.8 meter diameter metallizer* is controlled by a ladder logic hardware system illustrated in Figs. 2 and 3. When the deposition pressure is reached, the AL-PREFIRE TIMER(T1) shown in Fig. 2 activates control relay CR1 for a length of time which is manually set into the timer. This closing of the CR-1 relay seen in Fig. 3 applies a voltage to the TERMINAL STRIP. This voltage controls, through additional equipment, the voltage applied to the filament bus bar connections. The voltage on the bus bar causes current to flow through the filaments and the heat generated melts the aluminum charges hung in the tungsten coils. The level of the voltage is determined by the manually set position of the 3.5K potentiometer shown under AL-PREFIRE PWR ADJ on Fig. 3. This "prefire" phase is intended to be just long enough and hot enough to cause the aluminum to melt and wet the filament but not evaporate the aluminum.

When the prefire timer completes its cycle, the AL-VAPOR PWR TIMER(T2) shown in Fig. 2 activates CR2. This then applies a voltage to the TERMINAL STRIP in Fig. 3 which is determined by the setting on the AL-VAPOR PWR ADJ potentiometer. The filaments are then heated by this new higher voltage for a duration determined by the setting on timer T2. This "Al-vapor" phase is intended to just evaporate all of the aluminum at a high rate before the timer is done. It is desirable that the rate be as high as possible while still allowing enough time for any rotating fixtures loaded with parts to expose all of the necessary surfaces for adequate coating. Continued heating of the filaments after all of the aluminum has been evaporated shortens filament life and may deposit evaporated tungsten on the parts.

This sort of metallizing is being done satisfactorily many times a day in hundreds (if not thousands) of chambers around the world. However, if a part configuration has a deep cavity and steep sides, such as that shown in Fig. 1, there is much less

* Stokes Vacuum, Inc., Philadelphia, PA

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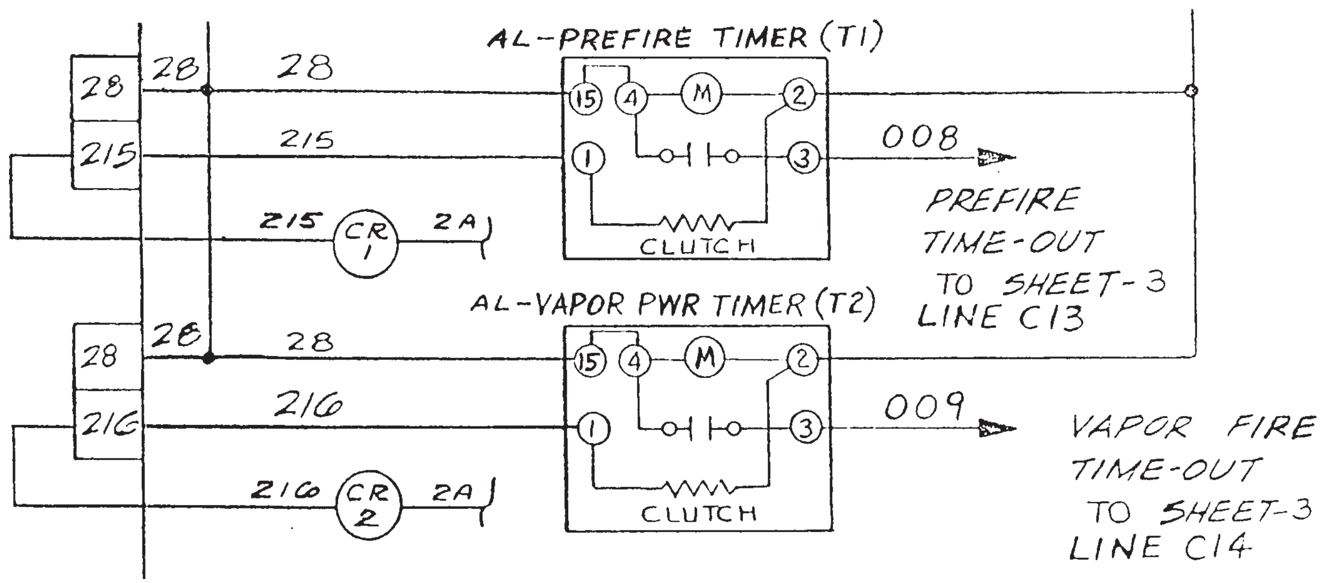

Fig. 2. Timing control section of metallizer ladder logic.

margin for error than in the more common cases. The settings of the AL-PREFIRE PWR ADJ and the AL-VAPOR PWR ADJ potentiometers seem to be one of the weakest links in the reproducibility of the case in question. A few degrees of difference on a potentiometer rotation from one firing run to another can make a significant difference in the voltage applied to the TERMINAL STRIP. We discovered the opportunity described below to solve this reproducibility problem and have additional flexibility in the filament heating profile versus time.

THE OPPORTUNITY

A quartz crystal process controller existed in connection with this particular metallizing chamber from previous experiments for which it was no longer required. Such units are normally used to control rates and coating thickness with programmable capabilities as illustrated in Fig. 4. Typically, a process can be programmed which controls the output voltage profile with ramps and soak times and which controls the deposition rate and thickness. The thickness versus time is determined by the change in frequency of a vibrating crystal as material is deposited on its surface. A shutter can be

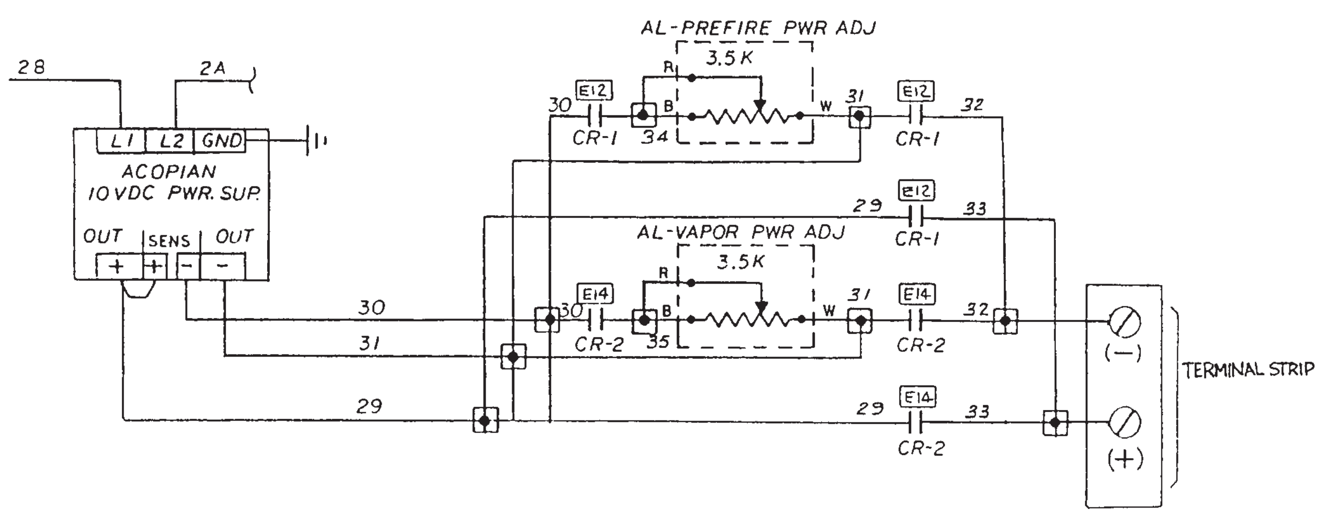

Fig. 3. Voltage control section of metallizer ladder logic.

opened after two different warm up ramp times and soak times have been completed. The PID loop control voltage output is automatically adjusted to give the programmed deposition rate, and the thickness of the deposited coating is monitored by the crystal readings. When the programmed thickness is reached, the shutter is closed and the power can be ramped down to an idle level while waiting for the next deposition cycle. In the particular controller used*, it is also possible to ramp up or down to a new rate during deposition, if desired.

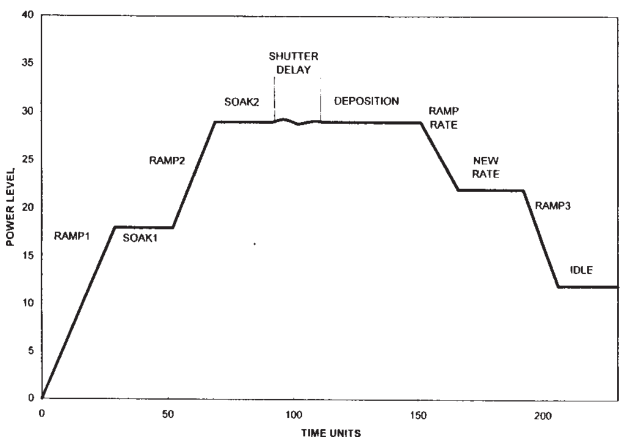

Fig. 4. Typical crystal controller power profile with time.

As described below, the capabilities of this controller are used to gain greater reproducibility and flexibility by replacing and augmenting the functions of the potentiometers and timers of the metallizer.

THE APPROACH

The crystal controller is integrated into the system as shown in Fig. 5. The normal lines (32 and 33) to the bus bar voltage controlling TERMINAL STRIP on the right are reconnected through a DPDT switch so that the metallizer can function either in the original mode or under the signal voltage from the crystal controller.

The signal to start the controller cycle is provided by the addition of a relay which is activated by the same voltage which activates CR1. It makes contact between Pin 9 and Pins 13, 14, and 15 on the crystal controller which starts the selected process program. If the DPDT switch is in the position to apply the controller voltage, the programmed output of the crystal controller (0 to 10 volts) goes to the TERMINAL STRIP.

Since the metallizing process normally evaporates the complete charge of aluminum from the filament in each firing, there are no shutters in the metallizers. The thickness of the coating is determined by the amount of the aluminum charge, and therefore, the crystal thickness monitoring aspect of the controller is not required or desired. The thickness monitoring aspect of the controller is overridden by programming a requirement for zero (0) deposition thickness. This then reduces the SHUTTER DELAY, DEPOSITION, RAMP RATE, AND NEW RATE times seen in Fig. 4 to zero (0). A dummy crystal is connected to the controller (external to the chamber) so that the control unit always has a good crystal signal which never increases in its thickness indication. This is necessary to overcome an indication of a "bad crystal" which would inhibit the program from executing.

In this new mode of operation, three ramp (or rise) times, three soak power levels, and three soak times are available to be programmed as illustrated in Fig. 6. The third soak power and soak time are used in a way which was probably not intended by the designers of this controller. These times are actually the RAMP3 and IDLE of Fig. 4. There is no idle time

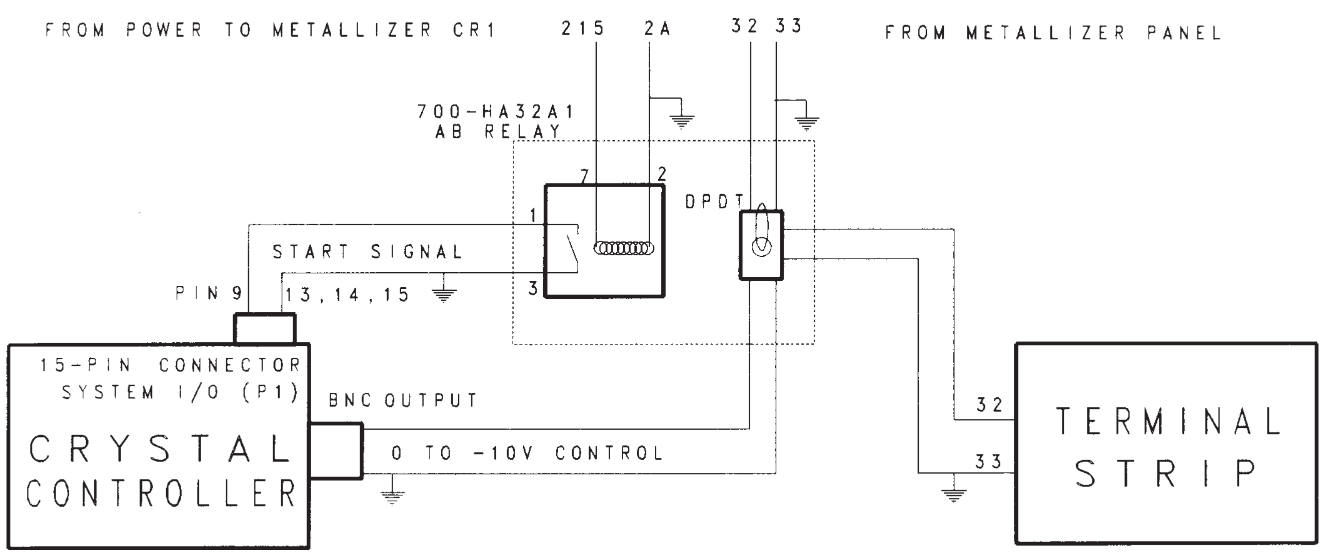

Fig. 5. Integration of the crystal controller to the metallizer.

* STC-200, Sycon Instruments, Inc., Syracuse, NY

available to be programmed on the controller. However, the Soak Power 3 is set to the desired level and then the Max Power Limit is set to the same power level. The time at this maximum power is then limited by programming the Max Pwr Dwell time. The controller is programmed with “Abort Max Pwr Sw ON”, it will then stay at this maximum power level for only the specified dwell time and then turn off the control voltage. This terminates the firing.

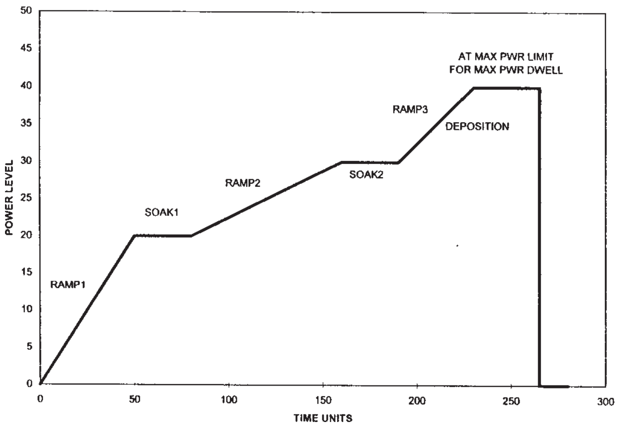

Fig. 6. Variables available to program in the controller.

Table 1 shows the pertinent values of the typical program illustrated in Fig. 7. This program closely simulates the original usage of the timers T1 and T2 with the two potentiometers. Here, the voltage is quickly brought to the SOAK1 level. If SOAK2 were the same as SOAK1, this would be essentially the same as the original AL-PREFIRE PWR ADJ ; the time equivalent of AL-PREFIRE

TABLE 1
TYPICAL (SELECTED)
CONTROLLER PARAMETERS

Setpoint Thk Lim	0.000 KA
Setpoint Time Lim	0:00 M:S
Soak Power 1	23.0%
Rise Time 1	0:01 M:S
Soak Time 1	0:01 M:S
Soak Power 2	25.0%
Rise Time 2	0:30 M:S
Soak Time 2	0:01 M:S
Soak Power 3	40.0%
Rise Time 3	0:03 M:S
Deposit Rate	0 A/S
Rate Ramp Mode	OFF
Max Power Limit	40.0%
Abort Max Pwr Sw	ON
Max Pwr Dwell	0:17 M:S

Table 1. Typical pertinent parameters in the controller.

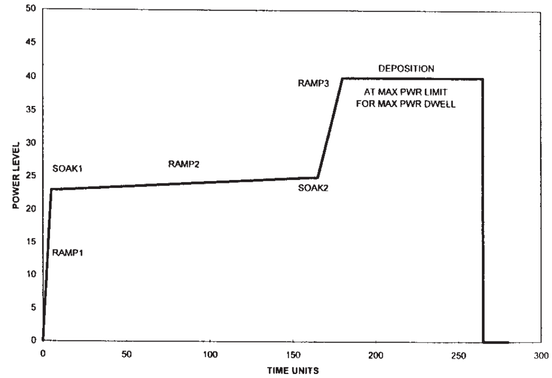

Fig. 7. Program simulating original timers and powers.

TIMER(T1) would then be the sum of the times of RAMP1, SOAK1, RAMP2, and SOAK2. If RAMP3 were short, the sum of RAMP3 and MAX PWR DWELL times would be the same as AL-VAPOR PWR TIMER(T2) and MAX PWR LIMIT would be the same as the AL-VAPOR PWR ADJ. In the new operating mode, the T1 timer is set to be a few seconds longer than the total process time of the crystal controller since the CR1 relay activates and sustains the controller output. The T2 timer does not come into use at all in the new operating mode.

The original equipment had four (4) variables and a certain practical limitation on reproducibility of the two potentiometer settings. The new configuration offers nine (9) variables and therefore greater flexibility in addition to greater reproducibility of the control voltage. The crystal controller offers the additional advantage of storing many process programs.

DISCUSSION

The challenges of aluminum metallizing were mentioned above. These are dominated by the need for a highly reflective coating which generally implies a coating thick enough to cover the substrate in the area of the part where the coating is the thinnest. However, there are also undesirable effects when the coating is too thick in other areas. High angles of incidence from the surface normal of the depositing aluminum are also to be avoided as a contributor to the brownish “burned” appearance. Problems result from “balling” of the aluminum charge on the filaments. This may be represented by the aluminum not wetting the filaments evenly, aluminum dripping from the filaments, and/or material not being totally evaporated by the end of the cycle. Problems also result if the filaments are heated for any significant time after the aluminum has all been evaporated. Balling and excess heating times primarily impact the useful life of the filaments and thereby the impact process costs, but they can also impact the quality of the coating.

The resistance of the filaments used are typically on the order of 0.1 ohms and approximately two dozen (24) filaments may be connected in parallel across the bus bars. This implies that the resistance measured at the terminals of the bus bars would be on the order of 1/240 ohm. If 10 volts were applied to this bus bar, this would produce a current of 2400 amps. If there happened to be a contact resistance of 1/480 ohm at one of the contacts for the voltage applied to the bus bars, the current flow at 10 volts would be reduced to 1600 amps! To regain the 2400 amps desired, it would be necessary to raise the voltage to 15 volts. A similar argument could be made with respect to the contact resistances of the connections of the filaments to the bus bars. It would appear that providing a reproducible current from run to run would be more desirable than a reproducible voltage. This would at least compensate for contact resistance variations where the voltage is applied to the bus bars. This would require a current sensor and a circuit to regulate the current to match the level called for by the program from the controller. We have not yet implemented such an addition.

The improved control of the voltage from run to run allows further process refinement. It is practical to use Design of Experiments (DOE) methodology to find the best controller program parameters to give the required part coverage, high reflectance, and long filament life. Although it is beyond the scope of this paper to discuss this in great detail, what has been done and what could be done will be briefly discussed.

The simplest firing process for either the old system or the new would be “Direct Firing”. This is where a constant voltage is applied for a specific length of time. The filaments would heat up as fast as the voltage allowed, the aluminum would melt and wet (as best it could) and be further heated until it all evaporated. Only the voltage and the time need to be optimized with respect to the results of interest. When evaporating a charge large enough for the minimal thickness and reflectance required, these results would include the avoidance of: balling, heating past the point of total evaporation, “burning” effects. DOE methodology could be used to optimize these parameters with respect to the desired results with a minimum number of experiments. If a reasonable maximum and minimum for each of the two parameters is known, then a thorough optimization could be done using the Central Composite Design (CCD) with twelve (12) test runs. A simpler set of just five (5) runs might be adequate if quadratic effects and run-to-run variations could be ignored.

The typical firing process has the prefire and vapor phases which each have their own time and voltage settings. A similar program can be used in both the old and the new control configurations. Either would have the four (4) variables to be optimized versus the same desired results as above. A Box-Behnken design from DOE would require 27 test runs to be able to estimate all linear, all quadratic, and all 2-way linear interactions. The results could then be optimized based on this information.

Given the full flexibility of the crystal control system, there are nine (9) variables to be optimized. It might be interesting to experiment with a decreasing slope for RAMP2 so that the heating power reduced as the aluminum started to melt and wet the tungsten. This might allow more even wetting, avoid balling, and better prepare for the final RAMP3 and deposition time. We have not tried this yet. A practical optimization of the possibilities with nine (9) variables would exercise most of the art and science of the DOE methodology. Just a full-factorial set of runs to determine the two level linear interactions would require 2^9 or 512 test runs. Clearly, it is desirable to obtain results with significantly fewer test runs which would give reasonable confidence in yielding a process that is near optimal. Knowledgeable application of the DOE methodology should be able to give such results in approximately 50 test runs. We have not yet pursued these tests.

The variables using the crystal controller have been reasonably optimized as though the processes were the older four (4) variable type. Satisfactory and reproducible results have been obtained on a daily basis.

CONCLUSION

The original metallizing equipment had four (4) filament voltage variables and certain limitations on the reproducibility of the two potentiometer settings. The new configuration with the crystal controller provides nine (9) variables and therefore greater flexibility in addition to greater reproducibility. It also offers the additional advantage of storing many process programs to accommodate the different filaments and charges that might be needed for different products. This can be a significant advantage if a given metallizer is used for a variety of products.